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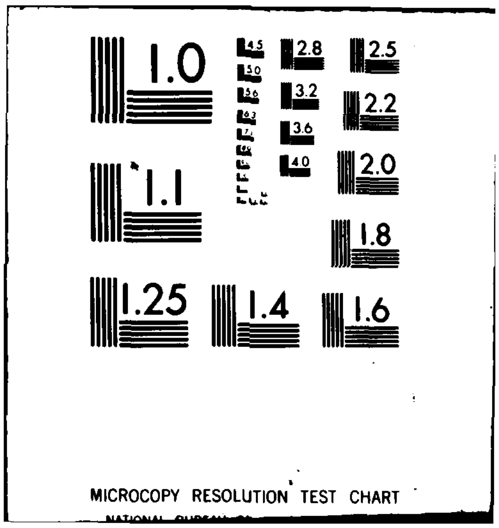

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Systems Research &
Development Service
Washington, D.C. 20590

A State-of-the-Art Survey of the Development of Taxiway Guidance and Control Systems

Charles A. Douglas

September 1982

Final Report

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No. DOT/FAA/RD-81/87	2. Government Accession No. AD-A117528	3. Recipient's Catalog No.
4. Title and Subtitle A State-of-the-Art Survey of the Development of Taxiway Guidance and Control Systems		5. Report Date September 1981
		6. Performing Organization Code NAEC 942
7. Author(s) Charles A. Douglas		8. Performing Organization Report No.
9. Performing Organization Name and Address Naval Air Engineering Center Lakehurst, NJ 08733		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DOT FA77WAI-786
12. Sponsoring Agency Name and Address Federal Aviation Administration Systems Research and Development Service Washington, DC 20591		13. Type of Report and Period Covered Final-September 1981
		14. Sponsoring Agency Code ARD-500

15. Supplementary Notes

The report was prepared by Kilkeary, Scott & Associates, Inc., 509 Powell Drive, Annapolis, MD 21401 under contract N68335-80-C-2008

16. Abstract

This study consisted of a review and analysis of the historical background of taxiway lighting and marking, its functions and development. The study emphasized the block control system used at Heathrow, the problems associated with manual and automated control of stop, hold and clearance bars, and the problems associated with automated surface movement control. The study provides the present status of developments and recommendations for future research endeavors.

17. Key Words	18. Distribution Statement
Airport Lighting Aids Taxiway Guidance Visual Aids for Airports Taxiway Lighting and Marking	Document is available to the public through the National Technical Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	39	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	[illegible]ter [illegible]acting	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

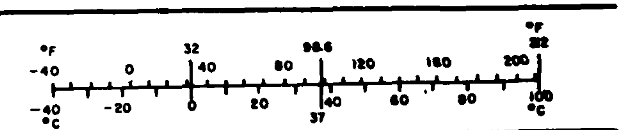

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADSEL	Selectively Addressed Secondary Surveillance Radar System
AGA	Aerodrome, Air Routes and Ground Aids Division of the International Civil Aviation Organization
ASDE	Airport Surface Detection Equipment
ASMC	Airport Surface Movement Control
ATC	Air Traffic Control
ATS	Air Traffic Services
CAA	U.S. Civil Aeronautics Administration, now Federal Aviation Administration
DABS	Discrete Address Beacon System
FAA	Federal Aviation Administration, Washington, DC 20590
GMC	Ground Movement Control
ICAO	International Civil Aviation Administration, P.O. Box 400, Succarsale; Place de l'Aviation Internationale, 100 Sherbrooke St., West, Montreal, Quebec, Canada H3A 2R2
ILS	Instrument Landing System
NAFEC	National Aviation Facilities Experimental Center, now FAA Technical Center, Atlantic City, New Jersey 08405
RAE	Royal Aircraft Establishment, Bedford, England MK41 6AE
RVR	Runway Visual Range
VAP	Visual Aids Panel of the International Civil Aviation Organization

GUIDANCE ON TAXIWAYS

1. INTRODUCTION

1.1 Scope

This report gives the results of a study of the historical background of taxiway lighting and marking with emphasis on problems of ground movement control conducted as part of Interagency Agreement DOT FA77 WAI-786 with the Naval Air Engineering Center, Lakehurst, New Jersey. The study was performed by Kilkeary, Scott & Associates, Inc., 509 Powell Drive, Annapolis, Maryland, 21401, under Contract N68335-80-C-2008. The study consisted of a review and analysis of the historical background of taxiway lighting and marking, with emphasis on the block control system used at Heathrow, the problems associated with manual and automated control of stop, hold, and clearance bars, and the problems associated with automated surface movement control.

1.2 Functions of Taxiway Lighting and Marking

Taxiway lighting and marking has two functions, 1) providing guidance between the runway and the apron and 2) transmitting instructions from airport traffic control to the pilot.

The guidance element should provide information which enable the pilot to:

a. Expeditiously exit from the runway to a taxiway.

b. Proceed to his destination along a route designated by airport traffic control.

c. Steer his aircraft expeditiously along the taxiway, around curves, and through intersections.

d. Positively identify holding points and clearance limits.

e. Identify his location on the airport.

The control element enables airport traffic control to direct the pilot to follow a designated route on the movement area and to stop at designated intersections and taxiway positions by visual means without using oral instructions transmitted by radio.

Note that the taxiway visual aids can be used to guide and control fire, rescue, and other vehicular traffic also.

2. DEVELOPMENT OF TAXIWAY GUIDANCE VISUAL AIDS

2.1 In the Beginning

In the 1930's when paved runways and runway-edge lights were becoming common, the runways themselves were available for most of the taxiing because traffic was light. Taxiways were usually short, leading from the apron directly to the runway as shown in Figure 1. The situation today is quite different, as illustrated by Figure 2.

In those days airports were usually floodlighted, and this lighting plus the landing lights on the aircraft provided sufficient guidance, especially when taxiway markings were provided.

2.2 Development of Taxiway Markings

2.2.1 Centerline Markings

The need for taxiway centerline markings developed during the early 1940's and specifications for these markings were written at that time [1, 2]. The markings were to be continuous yellow (to differentiate them from white runway markings) lines six inches (15cm) wide. At runway-taxiway intersections the markings were to continue through the intersections.

2.2.2 Exit Taxiway Markings

The need for exit taxiway markings was demonstrated by the flight tests in fog at the Landing Aids Experiment Station, where the taxiway markings did not extend onto the runway. As a result of the problems encountered during flight tests conducted in visibilities as low as 300 feet, the Landing Aids Experiment Station recommended that "taxiway markings be devised and standardized to give a pre-warning of turns and intersections". This recommendation was soon implemented and taxiway (centerline) markings curved into the runway marks were specified for exit taxiways [3].

2.2.3 Holding Position Markings

Holding position markings consisting of three yellow six-inch (15cm) stripes placed across the taxiway 100 feet (30 m) from the near edge of the runway were specified in 1944 [1]. This marking was changed by 1953, to markings of the present Category I holding position marking, consisting of two solid and two broken transverse lines with the solid lines indicating the side on which the aircraft was to hold, to remove the ambiguity in the direction of travel to which the marking applied. A single solid and a single broken line was used for other runways [4]. The need for another, distinctive, holding position marking arose with the introduction of Category II and III holding position marking [5].

In the U.S. holding position markings are now reinforced by type L-829 taxiway signs placed abreast of the markings showing ILS for precision approach runways, including runways instrumented with a microwave landing system and the runway number at non-instrument holding positions [6].

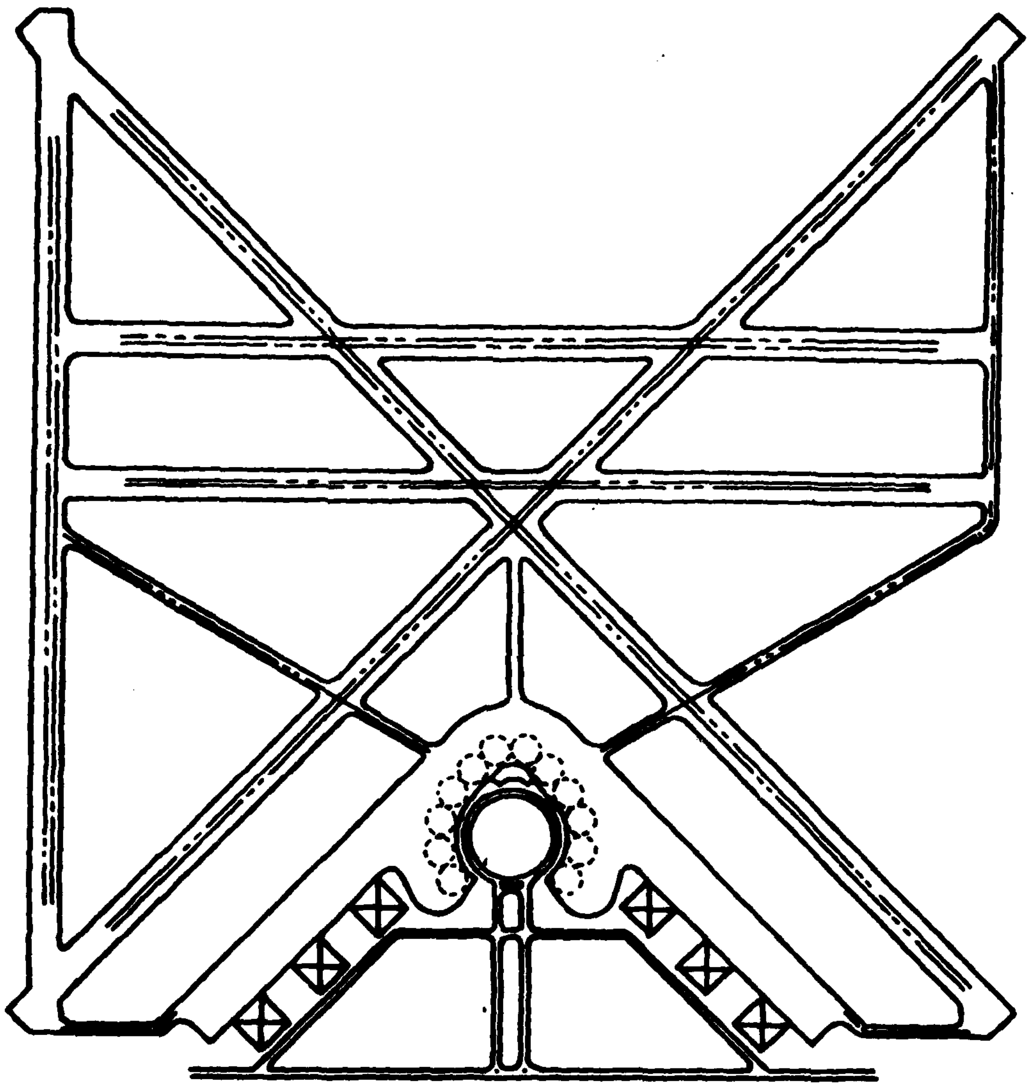

Figure 1. Plan of a representative airport illustrating the simple taxiway systems of the 1930's and early 1940's.

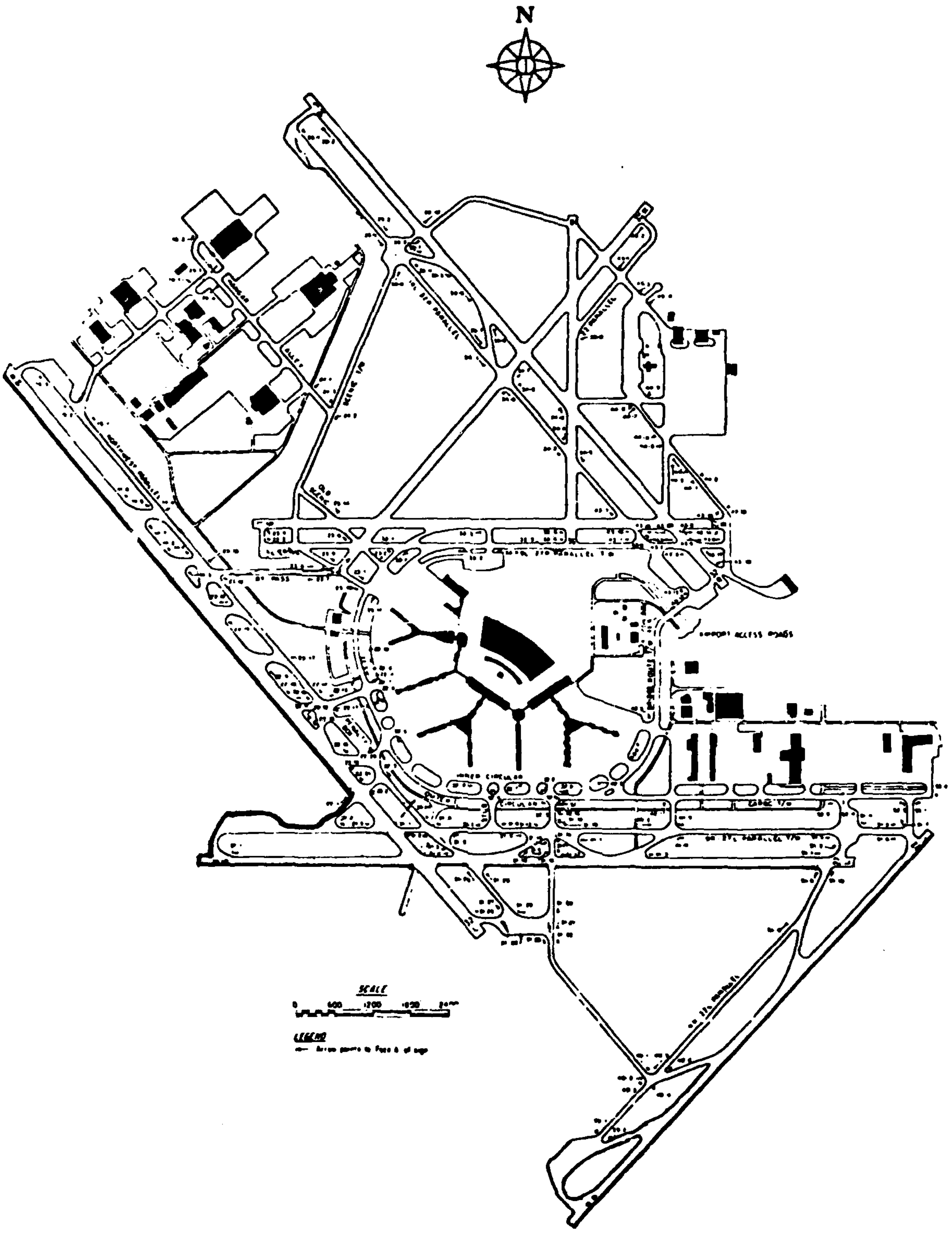

Figure 2. Visual ground aids at O'Hara International Airport (Runways 14L-32R and 14R-32L are Category II runways)

2.2.4 Taxiway Side Stripes

In 1970 the Visual Aids Panel recommended that specifications for taxiway side stripes be included in Annex 14 [5]. This recommendation was approved. These markings consist of a pair of solid lines six inches (15 cm) wide spaced six inches (15 cm) apart and are yellow. They are to be placed along the edges of taxiways, holding bays and aprons that cannot be readily distinguished from the load-bearing surface. These markings are specified for U.S. usage [6].

2.2.5 Markings for Unserviceable Taxiways

Crosses have been used for the identification of unserviceable taxiways, as well as unserviceable runways for many years [7].

2.3 Taxiway Lighting

2.3.1 Taxiway Edge Lighting

A search of the literature did not yield a firm date for the beginning of the use of taxiway lights. Breckenridge, in his 1937 paper "The Airport Lighting Specifications of the Department of Commerce" [8] makes no mention of taxiway lights. Moreover, figure 3 of that paper shows no chromaticity requirements for the color "blue". Similarly, British Standard Specification for "Land Aerodrome and Airway Lighting" of June 1937 does not mention taxiway lighting nor specify the characteristics of "blue" [9]. In addition, Civil Aeronautics Bulletin No. 10, "Airport Lighting" of September 1, 1938 does not list taxiway lights [10]. Hence, we can conclude that these lights were not used to any extent before 1938.

However, Specification AN-C-56 "Army-Navy Specification for Colors: Aeronautical Lights and Lighting Equipment", dated July 25, 1942, specifies the chromaticity requirements for "blue".

The inclusion of a specification of the chromaticity boundaries for blue light in Specification AN-C-56 [11] indicates that the choice of the color blue for taxiway edge lights was made in the period 1940-41. Calvert states that the color blue was chosen during World War II because it gave the best security aginst the operation of intruder aircraft [13]. However, a more likely reason, at least in the United States, is that blue was the only recognizable color not being used on airports. The human eye can recognize only four, or at the most five, colors of lights which appear as point sources; red, green, blue, and white/yellow. The colors white and yellow can be differentiated from each other only when seen in close proximity in time and space, as with adjacent lights or alternately flashing lights. At the time the color blue was chosen, red was being used for obstruction lights and for some approach lights; green was being used for threshold lights and range lights, and white and yellow were being used for contact (runway edge) lights, leaving only the color blue available for the taxiway edge lights.

Obtaining a satisfactory blue color with a light using an incandescent lamp as a source requires that a glass lens or filter have a transmittance

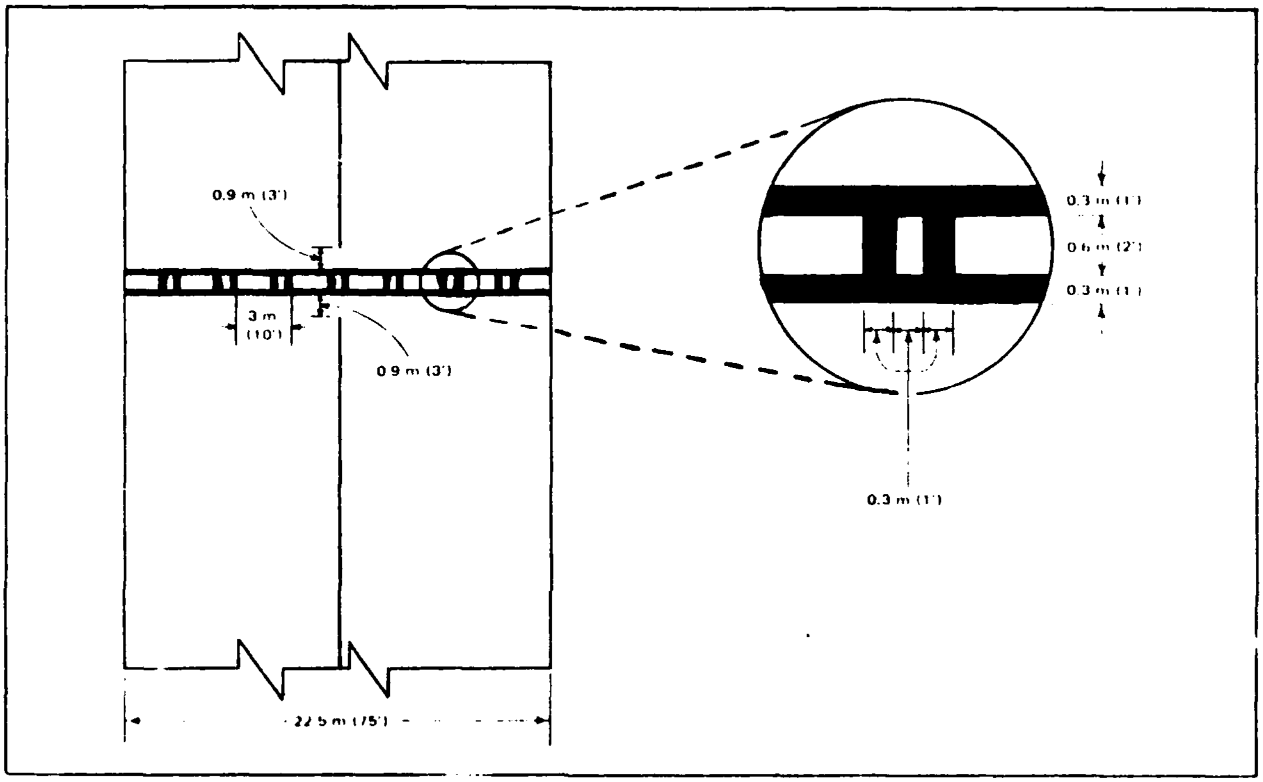

Figure 3. Category II or III holding position marking.

of 0.02 or less, a transmittance which is only one-tenth that of a red or green lens or filter. Hence, blue is the least desirable of colors insofar as intensity is of concern. However, the intensity requirements of taxiway-edge lights are not as severe as are the intensity requirements of runway end, threshold, and edge lights, and taxiway lights of satisfactory intensity could be obtained by adding blue filters to clear runway edge lights.

Semiflush lights, type AN-L-9, were to be used except that for snow areas the use of snow-area lights were suggested. Lenses producing asymmetrical beams were to be used on straight portions of the taxiway, and lenses producing symmetrical beams were to be used on exits, entrances, and curves [14].

Because of the high cost of installing semi-flush taxiway edge lights, retroreflective delineators were often used instead of lights during the 1940's. The Air Corps specified the use of such delineators, not lights, in 1944 [1] and continued using delineators into the 1950's. The carrier-based Navy aircraft of the period did not have landing lights. Hence the Navy, in permitting the use of delineators, stated that the system was "suitable for aircraft which have a light source in the vicinity of the cockpit " with the qualification that "In all instances a flashlight, or other light directed at the reflectors by the pilot will provide better visibility . . . .".

Taxiway edge delineators are still used at some low activity airports as a substitute for edge lights and at some high activity airports as a supplement to taxiway lights, especially to centerline lights on curves and at intersections.

Elevated taxiway lights were introduced in the mid 1940's, at the time elevated runway lights were introduced. These taxiway lights had only symmetrical beams [5] (as opposed to the Navy specification of asymmetrical beams for the type AN-L-9 semiflush lights used on straight segments of the taxiway) with a representative intensity of approximately five candelas. They were originally mounted on yellow cones to improve their conspicuity during low-visibility day-light conditions but the effects of prop-wash and jet-blast was so severe that the lights were soon mounted close to the ground.

2.3.2 Taxiway Centerline Lighting

Calvert, in 1947, analyzed the problems which would be involved in taxiing with future aircraft on future airports stating [13]:

> "The new civil airports now under construction in various countries are very large, and have wider runways and taxiways than those previously used. The taxiing routes are also more complicated and include many islands and open spaces. These changes have greatly increased the difficulty of providing visual taxiing aids which will ensure that the desired movement rate will be maintained in all atmospheric conditions, and it has become necessary to review the whole problem in order to see what changes have become necessary in the conventional layout."

"It appears from this discussion that the best hope of achieving rapid taxiing on wide taxiways in bad visibility lies in installing the lights up the middle instead of at the edges. With this arrangement taxiing should be possible in daylight in all conditions down to a meteorological visibility of 50 yards. At night, there is probably no lower limit in practice."

Calvert used perspective drawings in his analysis to show that centerline lights provided better guidance during low visibility conditions than did edge lights especially on curves and at intersections.

Green was chosen as the most appropriate color since: a) runway centerline lights were white: b) red was restricted to obstruction lights; the probability of confusing yellow taxiway lights with white runway centerline lights, particularly when the latter are dimmed, was unacceptably high; and the transmittance of blue filters was about one-tenth that of green filters.

Calvert's recommendations were followed in the conversion of Heathrow, London's major civil airport, and green centerline lights were used to mark taxiways there and also at Gatwick [16]. These lights had relatively low intensities, about 30 candelas, and were intended only for nighttime use.

The value of centerline taxiway lights was immediately recognized by other countries, and rapid implementation followed. Annex 14 was amended in 1958 to include green centerline lighting an alternative to blue edge lighting following the 1957 recommendation of the AGA Division of ICAO [17]. However, it was not until 1964 that the U.S. evaluations were completed and the preparation of a Selection Order was recommended [18]. In 1972 the Visual Aids Panel recommended that Annex 14 be amended to specify centerline taxiway lights as a Standard for taxiways intended for use in Category III visibility conditions [19].

2.3.3 Exit Taxiway Lighting

2.3.3.1 Low-Speed Exits

The problem of lighting low-speed exit taxiway has been a long standing one. Many methods to solve this problem have been proposed, tested, and found wanting. The problem is more than that of marking the location of the exit. Guidance during the turn from the runway into the exit taxiway must be provided also. Douglas recently completed a detailed study of exit taxiway lighting [3]. He concluded that the use of green lights installed in the surface of the runway on the extended taxiway centerline marking is the only method which has received general acceptance. This method is in widespread use, and provision for such usage has been considered several times by the Visual Aids Panel. In 1966 the Panel recommended that marking low-speed exits by use of green lights be included in Annex 14 as a recommended practice [20]. However, centerline lights are not used to mark low speed exists at U.S. civil airports because of concern over the possible confusion of a low-speed exit for a high-speed exit. Studies made recently at NAFEC showed that using a green-green-yellow pattern of lights extending onto the runway was an effective method of differentiating a short-radius

exit from a long-radius exit; that the intensities of the yellow and green lights should be balanced; that wide-beam spread (L-852W) taxiway centerline lights were satisfactory for this application; and that where the use of lights is not justified, semiflush retroreflective markers in a similar color pattern will provide the required visual guidance [21]. The results are in agreement with the results of earlier FAA studies made in 1964 [18], 1970 [22a], 1972 [22b] and 1978 [23]. Several alternative methods of marking exits have been tried [3, 23], and even today the possibility of using flashing blue lights on either side of the exit is being tested at the FAA Technical Center. To date, none of these has been found to provide adequate guidance.

2.3.3.2 Long-radius, "High-speed," Exits

Green centerline lighting for long-radius exits was introduced at Gatwick airport (London's second airport) in the late 1950's.

Tests of centerline lights on long-radius exits were conducted for the Air Modernization Board at McClellan AFB by the Institute of Transportation, University of California at Berkeley in 1958. Low-intensity (1 to 10 candelas), closely spaced white or "blue" lights were used. Tests were seen only in clear weather. The tests indicated that the most effective daytime guidance was a one-foot wide yellow reflectorized stripe; that white was the preferred color for lights, and that the continuous line effect of the closely spaced lights deteriorated very rapidly at light spacings in excess of 40 feet, and the guidance effect was best at a spacing of 10 feet [24].

The Visual Aids Panel considered the problem of lighting these exits in 1962 and found that centerline lights were necessary and that they should be extended onto the runway and run parallel to the runway centerline for at least 200 feet (60 m). Some Panel members preferred the use of white, instead of green lights [25].

In 1962, the Aerodrome, Air Routes, and Ground Aids Divison of ICAO (AGA) recommended that the use of white be specified as a Standard in Annex 14 [26], which was adopted. However, in 1964, the Visual Aids Panel again considered changing the color specified in Annex 14 to green and found that it was premature to amend Annex 14 and that further tests were required.

Tests conducted at Dulles International Airport in simulated Category III visibility conditions showed that most pilots of aircraft off-set 30 feet from the runway centerline, on the side of the centerline of the long-radius exit, mistook the white exit lights for runway centerline lights even though the exit light spacing was 12.5 feet and the runway centerline spacing was 25 feet. Significant signs of this confusion existed for all simulated visibility of the centerline lights between 200 and 1000 feet with the problem increasing as the visibility decreased. Use of green exit lights, with a 12.5 foot spacing, reduced the maximum visibility at which confusion occurred to 500 feet. Green exit lights used with a 50 foot spacing eliminated the confusion for simulated visibilities of 200 feet and more [27]. On the basis of these findings, the Visual Aids Panel in 1966 recommended that the color specified for long-radius exit lights be

changed to green, the color originally used at Gatwick, even before the results of the tests at Dulles were formally reported [20].

2.4 Taxiway Guidance Signs

2.4.1 Development of Signs

As airports become larger and more complex and as air traffic become more congested in the years following World War II, the need arose for more routing and destination guidance than could be given by oral communications from the control tower, and signs began appearing at some major airports. To meet this need the Technical Development Center of the Civil Aeronautics Administration, in 1952, developed an elevated sign for use at taxiway intersections and as an exit marker replacing double blue lights at runway exits [28], and a taxi guidance system using these signs for guidance. [29] Simultaneously signs of basically the same type was recommended in a study conducted for the Navy [30]. These studies provided the basis for the specification of the type L-829 sign, issued in 1955, and the legends which were to be used. (See Figure 4) A bright future was forseen for these signs. For example, Vipond stated, "Rolling down the flat surface of a runway, a pilot often sees a confused jumble of blue lights off to the side. Perspective plays tricks on him. But there's no mistaking a sign with a brightly lighted arrow and legend" [30]. However, these signs met with almost instantaneous pilot objection, one of the criticisms being the small size of the signs [32a].

The type L-829 signs were designed for use both as directional signs and as intersection locators. This duality of purpose required compromises in design which affected their suitability for both uses. Marking intersections and the points of tangency of exits required that the signs be low so that they could be mounted close to the edge of the taxiway or runway. This limited their size. These signs were required to be legible at a distance of 500 feet. To accomplish this, the legends were comprised of lighted letters on a black background and the luminance of the letters was limited to approximately 50 footlamberts [28]. The result was a sign that was of limited conspicuity. Larger signs have since been developed and found to be more conspicuous and to have a greater legibility distance that the type L-829 sign [32b, 33]. One of these is now designated as type L-858, shown in Figure 5 [34]. However, these signs are so large that they cannot be placed sufficiently close to the runway edge to serve as exit locators.

Efforts have been made to obtain large signs sufficiently frangible as that they can be placed close to the runway edge. Inflated signs and "styrofoam" signs have been constructed [35]. However, these signs have been found unsuitable because of complexity, damage from jet blast, and damage to jet engines when pieces of a sign hit by an aircraft are ingested.

2.4.2 Color Coding of Taxiway Signs

In 1969, Bonaventura proposed that signs be classified according to function and that these classes be color coded [36]. He proposed the following classification and coding:

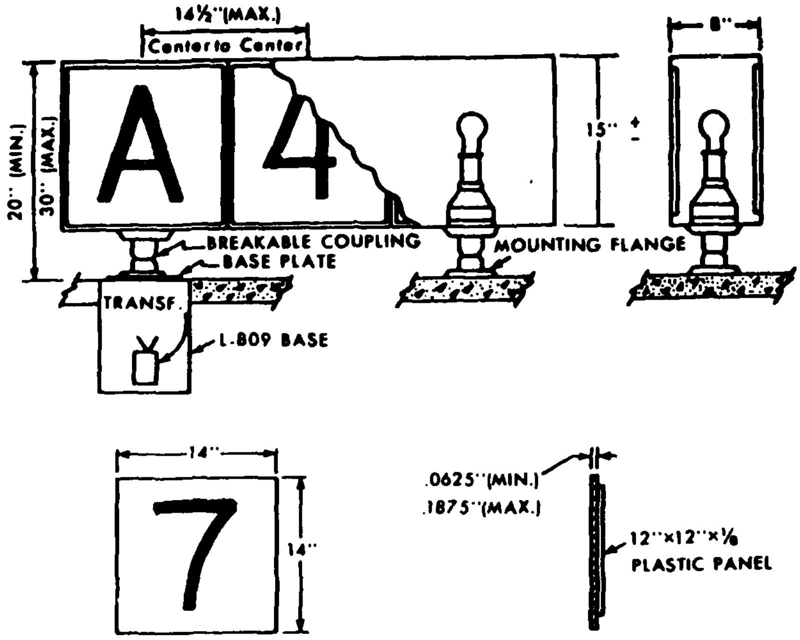

Figure 4. Type L-829 taxi guidance sign.

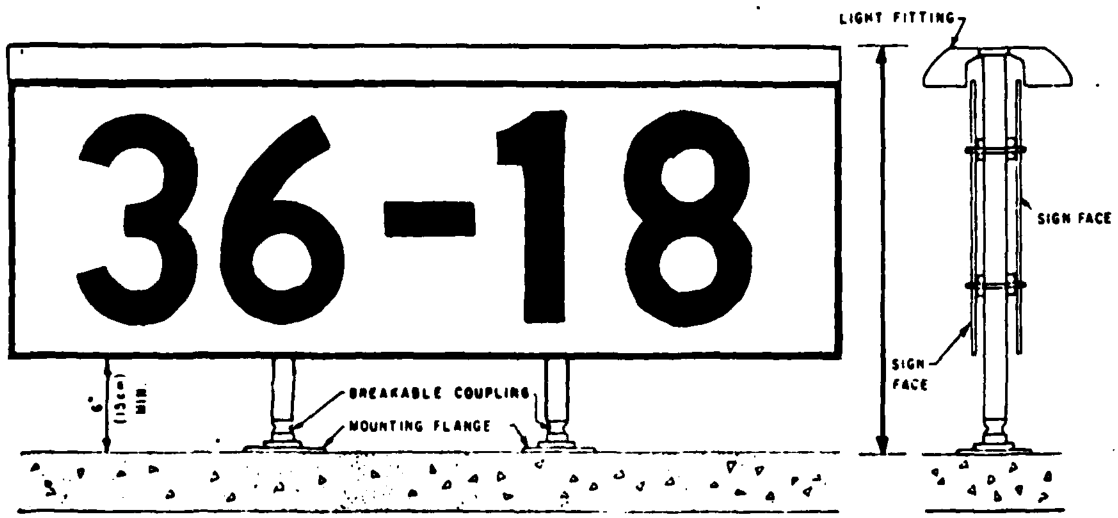

Figure 5. Typical type L-858 sign.

a. Mandatory: Those signs "which, if ignored could cause a hazard to aircraft in flight."

b. Informational: Those signs "which contribute toward safe and efficient taxiing."

c. Convenience: Those signs "which are used for locating specific services within the ramp area."

Bonaventura's proposal was tested at NAFEC and the color coding selected was [37]:

Mandatory: White inscription on a red background.

Informational: Black inscriptions on a yellow background.

Convenience: White inscriptions on a green background.

This coding was adopted for use in the United States.

This color coding system was presented at the Fifth Meeting of the Visual Aids Panel [5], and again at the Sixth Meeting [19]. The Panel was reluctant to act as the color coding used on highways had been adopted by several States. However, at its Seventh Meeting, the Panel recommended that Annex 14 be amended to specify Mandatory signs with a white inscription and a red background as a Standard. These signs to indicate, as a minimum, STOP, NO ENTRY, CAT II and CAT III and were to be lighted when intended for use at night or during conditions of low visibility. Non-Mandatory signs were also recommended for specification as a Standard when it was intended to indicate a specific location or destination on the movement area. The Non-Mandatory signs were to be either black inscriptions on a yellow background or yellow inscriptions on a black background and were to be lighted or coated with retro-reflecting materials if intended for use at night [38]. These recommendations were approved.

With the issuing of "Specification for L-858 Taxiway Guidance Signs", the U.S. has eliminated the Convenience class and now specifies [34]:

Type 1: Lighted signs with a white retroreflective legend on a red retroreflective background;

Type 2: Lighted signs with a black legend on a yellow retroreflective background; and

Type 3: Unlighted signs with a black legend on a yellow retroreflective background.

No specifications are now given for Convenience signs.

2.5 Clearance and Hold Bars

ICAO defines clearance bars as bars consisting of at least three yellow lights disposed symmetrically about and at right angles to the taxiway

centerline. They are used at taxiway intersections where there is no need for the STOP and GO signals provided by stop bars. Since the U.S. does not presently use stop bars, clearance bars are installed at some runway/taxiway intersections to reinforce the HOLD marking. These bars have been called "hold bars" in some recent documents [37, 40].

The use of clearance bars originated in the U.S. in the mid 1960's. (No report describing their development has been located.) Their purpose was to warn pilots of an approaching taxiway intersection and to indicate where to hold to provide adequate clearance.

In 1970, in response to a U.S. proposal, the Visual Aids Panel recommended that Annex 14 be amended to include the provision for clearance bars as a Recommended Practice [5]. This recommendation was approved.

Surprisingly, no provision for clearance bars is made in any Advisory Circular, other than Figure 2 of AC 150/5340-19 which shows both clearance and hold bars and contains a brief explanatory note [40].

2.6 Stop Bars

Stop bars consist of a row of red lights located across the taxiway at the point where it is desired that traffic stop. They are used to replace holding position markings or at taxiway intersections to provide control of traffic by visual means instead of voice communications, particularly in low visibility. The provision of stop bars requires their control by airport traffic services.

Stop bars were first used at Heathrow in the mid 1950's. They were located at the end of each block of taxiway lights and at runway entrances and switched by the ground controller to direct traffic. Because of the low intensity of the original semi-flush fixtures, stop bars were at first supplemented by red or white lights located on the tops of taxi guidance signs [16].

By 1970, considerable experience had been gained in the use of stop-bars and the Visual Aids Panel recommended that provision for stop bars be included in Annex 14 [5]. This recommendation was approved and Annex 14 was amended to include stop bars as a Recommended Practice.

The U.S. has not used stop bars because of the requirement that they be controlled by air traffic services. Instead, yellow hold bars are installed at some runway entrances and taxiway intersections. (See Section 2.5.)

3. USE OF VISUAL AIDS FOR AIRPORT SURFACE MOVEMENT CONTROL (ASMC)

3.1 Function of Airport Surface Movement Control

In its broadest sense, ASMC means the measures necessary to prevent collisions and to ensure that traffic moves smoothly and efficiently. It provides control of aircraft from the landing runway to their parking

positions on the ramp and back to the take-off runway; of aircraft moving between the ramp and maintenance or service; and of vehicular traffic on the maneuvering area. The control system uses, as appropriate, visual aids, voice communications, standardized procedures for routing instructions and control at intersections [41, 42]*.

The use of visual aids to perform a control function means that the aid is switched ON or OFF to provide specific instructions to a specific aircraft or vehicle. Thus the signal performs a control function, as would specifying a route by lighting only the lights on the taxiways comprising this route. A lighted HOLD sign does not fully perform a control function unless it is switched OFF whenever an aircraft is cleared through it.

3.2 Use of Visual Aids for Surface Movement Control in the U.S.

In the U.S., control of surface movements on the maneuvering area is accomplished almost exclusively by voice communications. The signalling lamp and, to some extent the HOLD marking lights, and signs are the only visual aids used to perform control functions in the U.S.

3.3 Use of Visual Aids for Surface Movement Control in Other Countries

The use of selective switching of taxiway lights and of stop bars (which require switching) is increasing at airports of other countries. The most highly developed system using visual aids for ASMC is that of Heathrow Airport.

3.4 Taxiway Guidance and Control at London (Heathrow) Airport [16, 19]

When the visual aids system for Heathrow (then called London Airport) was being designed, Calvert considered the fundamental problems of guidance and control, particularly during periods of low visibility, [13] stating;

> "The pilot of an aircraft taxiing on a large aerodrome with wide featureless runways and taxiways is in a somewhat similar position to a fly crawling on a blackboard. In good visibility he can see the edges of the runways and taxiways, and can obtain aiming points by noting where these vanish on the horizon. As visibility get worse, the edges become indistinct, all distant aiming points are blotted out, and the pilot is reduced to following lines, just as a motorist in a fog follows a kerb."

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* Reference [41] "A Study of Ground Movement Control at Large Airports" by G.M. Hogg reports the results of a comprehensive study of taxiway control and guidance made by an RAE research team.

Reference [42] "Surface Movement and Ground Control Systems" was recently prepared by the ICAO Secretariat with the assistance of a Study Group.

These papers are excellent analyses of the requirements of guidance and control systems and should be consulted for more detailed information.

3.4.1 Taxiway Lighting

Thus selective switching for taxiway centerline lights was provided. The taxiways and runways*, were divided into blocks ranging in length from 300 feet (90 meters) to 1800 feet (540 meters), as shown on Figure 6. Note that, non-active runways at Heathrow are often used as taxiways. Green "centerline" taxiway lights were installed on these runways at a distance from the runway edge equal to half the width of a taxiway. Taxiways have been added since the airport was constructed as show in Figure 7, but the principles of design have not been changed.

The ends of each block are defined by red stop bars placed across the taxiways and red wing bars on the sides of runways.

When a stop bar is switched on by the controller, the green centerline lights in the block ahead of the stop bar are automatically switched off thereby providing redundancy in the STOP signal. Stop bars at other entrances to the block remain on and the block is isolated from other traffic.

Some 4500 lights and over 700 circuits are used in the taxiway lighting system.

3.4.2 Position Indicator Boards

The ends of each block are marked by position indicator signs showing the number of the block in which the aircraft is located and the number of the block immediately ahead, as shown in Figure 7. These signs are used by pilots to check or report their positions and designated by ground movement controllers a check point when there is conflicting traffic ahead.

3.4.3 Route Indicator Signs

As the intensity of the taxiway lights in the original installation was about 30 candelas, the lighting system did not provide adequate guidance in clear daylight conditions. Diagrammatic route indicator signs were used in combination with voice communication as the main means of route information by day. White lights, shown in Figure 8 and 9, indicated the taxiway to be used by lighting the appropriate light when remote control was provided or by placing the "wander light" in the appropriate position. Two red lights installed at the bottom of each sign were lighted by the controller when the route ahead was obstructed. The lights were used, as were stop bars, to indicate that the aircraft must hold until the lights were turned off.

3.4.4 Selective Control

A selective switching system is used to control the blocks and stop bars which are to be used. When a switch in the Control Tower is turned to ON, a light on the switch is lighted. After the appropriate relays operate and the selected lights are energized, the flow of current is reported back to the Tower, the appropriate light on a facsimile panel is lighted, and the light on the switch extinquished.

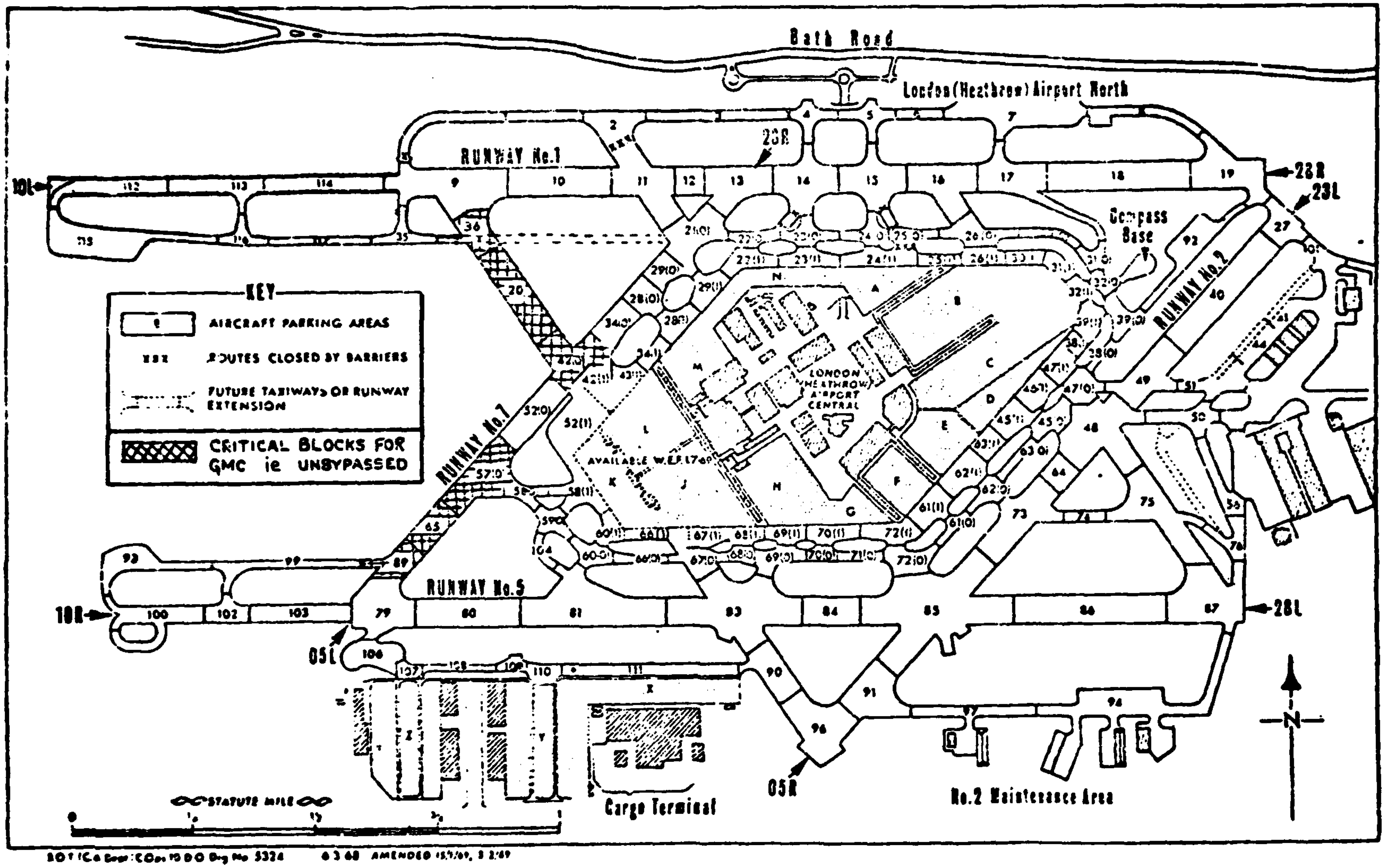

Figure 6. Location of traffic blocks at London (Heathrow) Airport, circa 1969. (From Reference [41])

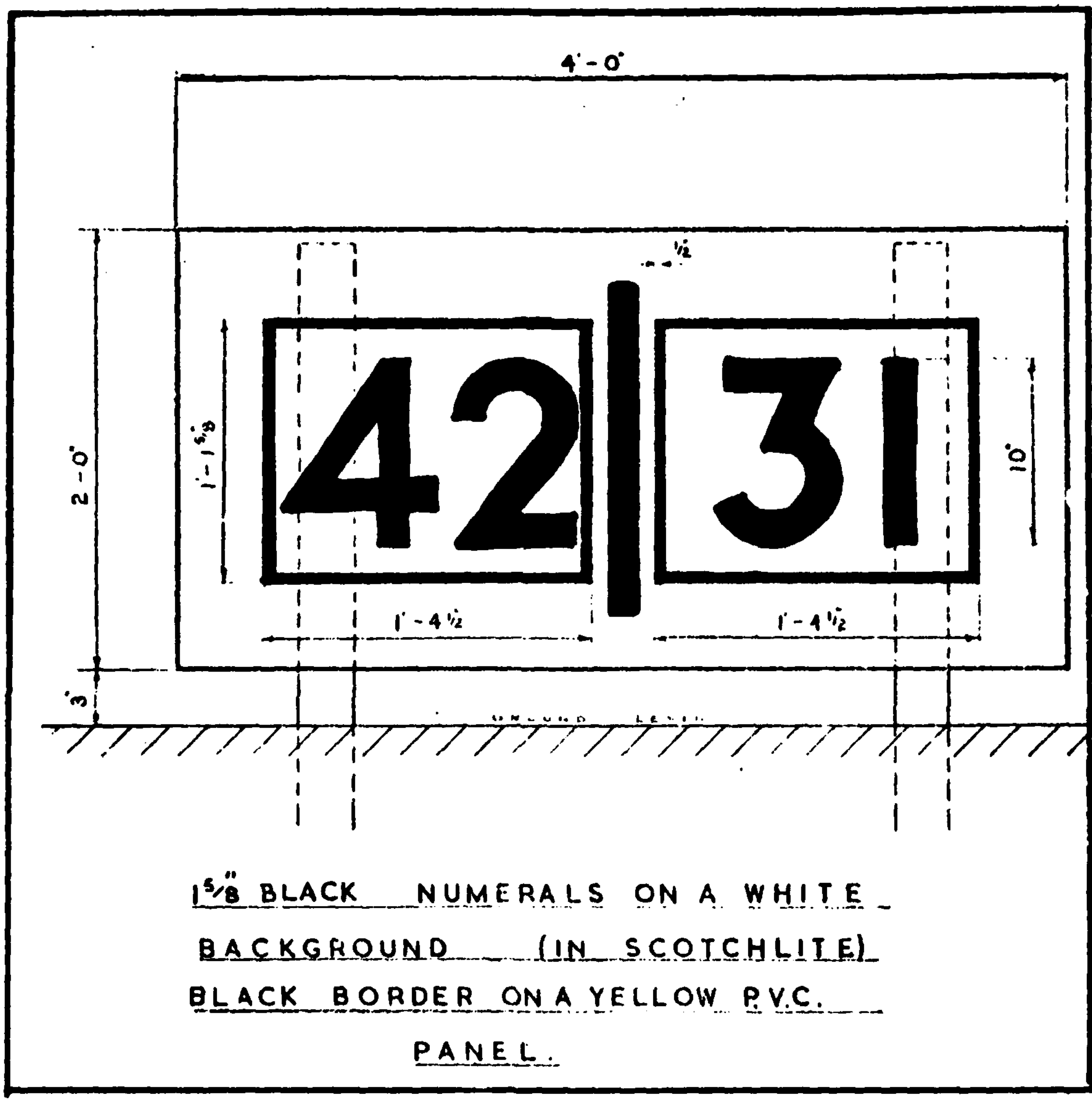

Figure 7. Typical Position Indicator Boards used at London (Heathrow) Airport. (From Reference [17])

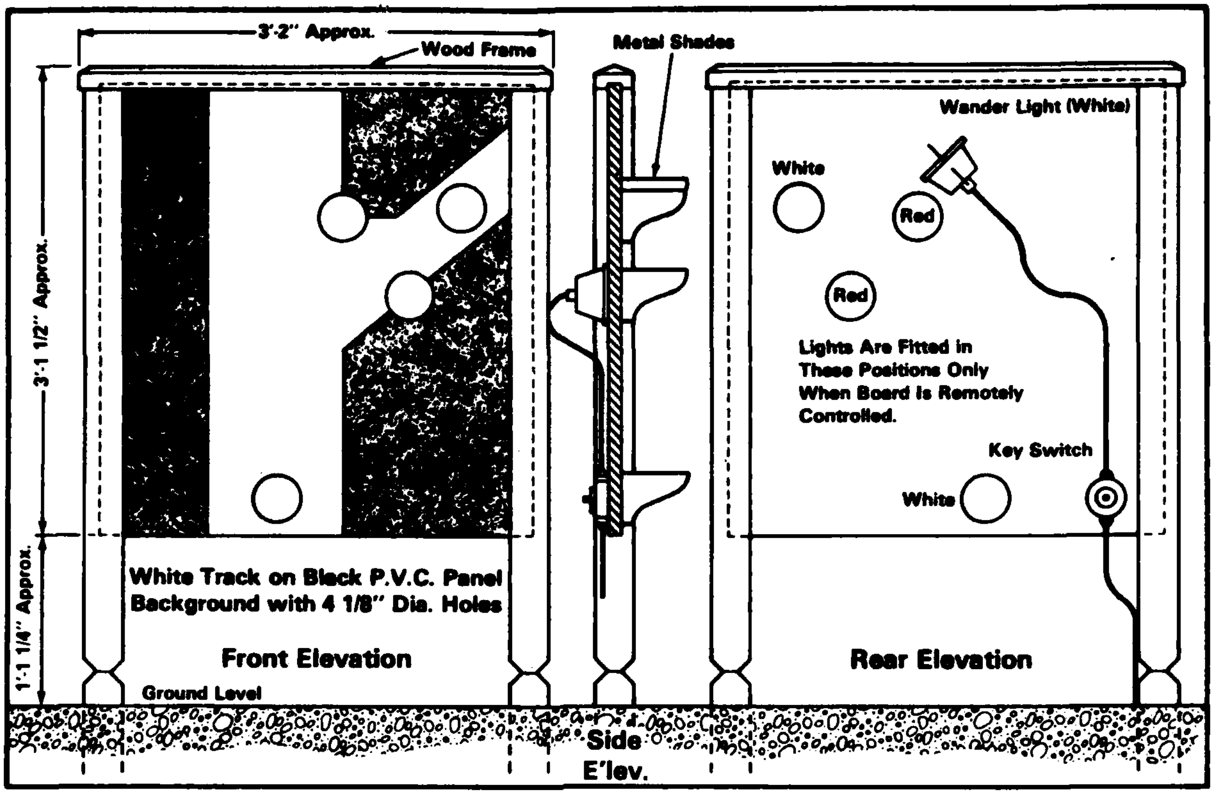

Figure 8. Daylight Route Indicator Board Used at London (Heathrow) Airport. (From Reference 17)

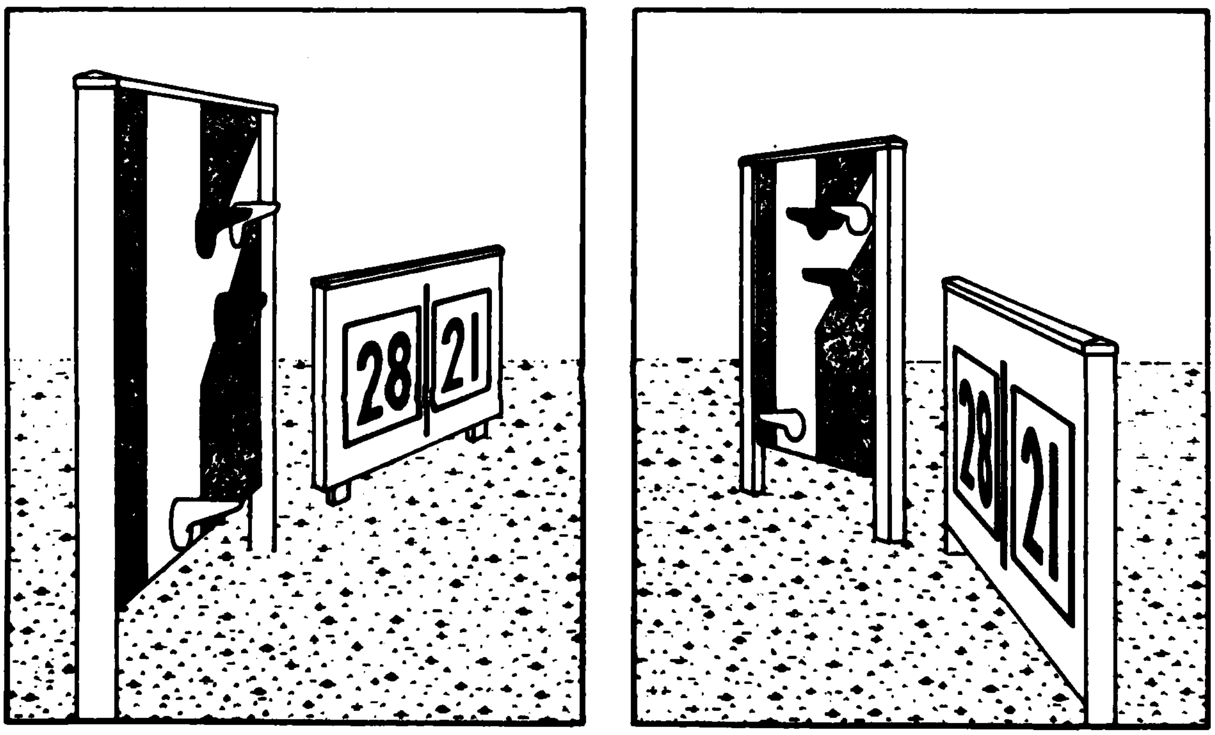

Figure 9. Typical Daylight Route Indicator and Position Indicator Boards at London (Heathrow) Airport. (From Reference 17)

3.5 Present Status

There have been no changes in the basic system of ground movement control at Heathrow since the system was introduced some 25 years ago. There have been a number of improvements made or planned. These improvements include the following. [43]:

a. Lighting fittings - Introduction of improved semiflush taxiway lights having peak intensities, in green and in red, of about 100 candelas makes possible the use of the switched taxiway lights for better guidance in daylight and in very low visibility conditions.*

b. Runway clearance lights - The purpose of these lights is to indicate to a pilot exiting a runway that he has cleared the ILS critical and sensitive areas. They are installed on both sides of the exit taxiways used in conjunction with Category III ILS to mark the edge of the ILS critical and sensitive area. They are white undirectional flashing lights directed toward the runway with an intensity of about 400 candelas and a flash rate in the range 30-60 flashes per minute.

c. Runway guard lights - These lights are provided to insure that there is no inadvertent infringement of the runway by aircraft or vehicles and a supplement to stop bars and holding position markings and signs. They have been used at Heathrow for several years and have been highly successful in alerting pilots and drivers of vehicles. They, which were originally flashing red lights, now are pairs of alternately flashing (wig-wag) yellow lights directed toward aircraft approaching the holding position. They are provided on Category III runways.

d. Taxiway intersection markings - These marking consist of double broken yellow line extending across the taxiway at taxiway/taxiway intersections to indicate a position of safe clearance between taxiing aircraft. (Note that the Visual Aids Panel at its Ninth Meeting recommended the use of a single broken line [44].)

e. Light spacing - Originally the taxiway lights were set at 80 feet (27 m) intervals [16]. The spacing is now 50 feet (15 m) on straight stretched and 25 feet (7.5 m) on curves with the closer spacing extending 200 feet before and after each curve. This spacing provides adequate warning of the proximity of curves down to an RVR of 300 feet (90 m), and confirms studies made by Smith using the BLEU simulator [45].

* New taxiway installations in the U.K. use fittings having intensities of about 250 candelas, meeting the requirements of Annex 14.

4.0 SWITCHING OF STOP BARS, HOLD BARS, AND CLEARANCE BARS TO LIMIT ACCESS TO RUNWAYS

4.1 Stop-Bars

4.1.1 ICAO Requirements [46]

Note: Throughout this discussion it has been assumed that the additional lights for stop bars recommended by Paragraph 5.3.20.2 of Annex 14 have been installed where required.

Stop bars are recommended for taxi holding positions and taxiway intersections where it is desired to supplement or replace markings with lights and, in addition, to provide traffic control by visual means. Paragraph 5.2.20.8 of Annex 14 indicates that the lights may be switched ON to indicate that traffic should stop and OFF to indicate that traffic should proceed.

Paragraph 5.3.20.3 of Annex 14 specifies that stop bars shall be provided at a holding position associated with a precision approach runway Category III.

At present the U.S. does not provide stop bars. Stop bars had been installed at Houston International Airport to protect the STOL runway from taxiing aircraft, but the color of these lights was changed to yellow (forming a hold bar) as controllers cleared traffic across the stop bars without switching them off [47].

Subsequently, in preparation for its Ninth (1980) Meeting, the Visual Aids Panel was alarmed to find that, in at least one State, that although the stop bars were intended to be switched off to indicate that traffic could proceed, the controllers were not doing so. The Panel stated that a lighted stop bar should have only one meaning, and that was that traffic should not pass until the lights of the bar were extinguished. The Panel called the attention of the Air Navigation Commission to the problem [44].

4.1.2 Reliability of Stop Bars

If the stop bar is to be used as a routine STOP signal, its operation must be completely reliable.

As Paprocki points out [48], if the pilot interprets an unlighted stop bar as a clearance to proceed, he may unknowingly intrude on an active runway in the event of a stop bar circuit failure. This problem was considered by the Visual Aids Panel at its Ninth meeting which referred to the reliability of interleaved circuits and secondary power making a failure highly unlikely. However, the Panel neglected to consider the more probable problems of failure, those in the control circuitry.

There are a number of ways to provide an auxiliary GO signal:

a. Verbal communications from the controller;

b. Switch the taxiway centerline lights on when the stop bar is not lighted and off when it is lighted as is done a Heathrow;

c. Provide a special auxiliary GO signal (The Visual Aids Panel did not consider such a signal necessary.)

In addition, the control circuitry should be arranged so that the stop bar is normally lighted and is turned off by the application of control power.

There is also the problem of human error. The controllers who were not switching the stop bar lights explained their actions by stating that they were afraid of not switching the stop bars back to ON after they had been turned off. This problem can be solved by providing an automatic return to ON after a period of about 15 seconds.

A monitor accuated by the current through the stop bar circuit should be provided. The system used at Heathrow appears optimum. See Section 3.4.4.

4.1.3 Manual vs. Automatic Switching of Stop Bars

Since stop bars must be switched, the only choice is between manual and automatic switching.

The stop bars controlling entrances to active runways should be under the direct control of the controller(s) responsible for these runways. Hence these bars should be switched manually.

Switching of stop bars at other intersections automatically implies automatic surface movement control. This subject is discussed in Section 5

4.2 Switching of Hold and Clearance Bars

As hold bars are a substitute for switched stop bars, if therc is a need for switching them they should be converted to stop bars by changing their color.

Clearance bars are intended to indicate the position at which an aircraft will be clear of an intersection and should not be used to transmit a command to stop. If such a command is needed, a stop bar should be installed. Hence, there is no need for switching them.

However, there is some advantage in using hold bar or clearance bars in conjunction with stop bars with a hold or clearance bar being lighted when its adjoining stop bar is not lighted. This procedure would provide a warning of the intersection or runway and would be especially useful when the visual surface movement control system is not being used.

5.0 FACTORS TO CONSIDER IN THE DEVELOPMENT OF AUTOMATED SURFACE MOVEMENT CONTROL

5.1 Background

In 1951 M.A. Warskow [49] stated,

> "As steady progress is made toward all-weather flying on a routine basis, it becomes apparent that more guidance must be provided to aircraft maneuvering on the airport surface. The pilot must be able to quickly guide the aircraft off the runway under the severe seeing condition of low visibility. He must then be able to navigate to his destination (sometimes two or three miles away over winding taxi routes) with a minimum of instruction from the control tower operator."
>
> "Electronic aids will be used to detect and track the location of aircraft on the aircraft surface, but visual aids can indicate the taxiway intersections with the runway, can provide navigational guidance along the taxiways, and can provide traffic control signals."

A little later, in 1957, Captain R.C. Robson[50] stated,

> "There is also the very real problem of what to do after the airplane is on the ground. From personal experience I can testify that it is a helpless feeling to land and then have to be towed to the terminal."

Since these statements were made, we have added taxi guidance signs, high speed exit marking and lighting, taxiway centerline lights with clearance and hold bars, at some airports, to our catalog of visual aids. Yet to be added are such aids as low-speed-exit lights extending on to the runway, runway clearance aids, closer spacings for centerline lights before curves to provide an advance warning of curves, stop bars with added lights when required, switched taxiway centerline lights or some other means of providing a positive GO signal, taxiway route definition by selective switching of taxiway centerline lights. These aids have been found necessary by operational experience, to support and control taxiway operations down to 300 foot (100 meter) RVR conditions.

It is apparent that in the U.S. the capabilities of taxiway lighting have not changed greatly in the past 30 years. Yet there are some in the U.S. who state that the present aids will be sufficient for operations down to 150 foot (50 meter) RVR conditions!

It is also apparent that improvement of the taxiway visual aids and the development of a manually operated surface movement control system of visual aids should be given precedence over the development of an automated system.

5.2 Recent Studies

There have been many studies of automated ground movement control over the years; for example, the TRACE (Taxiing and Routing of Aircraft Coordination Equipment) system [51] but no implementation in the U.S.

Most of the past studies are no longer pertinent. There is however, a very excellent comprehensive study of ground movement control conducted by a team of the Blind Landing Experimental Unit of the Royal Aircraft Extablishment and reported by G.M. Hogg in 1973 [41]. The conclusions of this study are considered valid today by those who made that study. Recently and ICAO Study Group prepared a Circular, "Surface Movement Guidance and Control Systems" [42] which provides a check on the currency of the RAI study. The discussion which follows is, for the most part, based on or extracted from these documents. However, it is not possible to summarize them within the scope of this study. The original documents are must reading for those planning future improvements in taxiway guidance and control.

5.3 General Considerations

All airports require a surface movement control system. However, each system must be related to the complexity, traffic density and weather of the airport. The control system should have a building-block capability so that it can be upgraded as traffic density increases or as visibility minimums are lowered.

Surface movement control is facing growing problems in high movement, clear weather conditions and also in low visibility conditions. Most of these problems could be overcome by a high-technology, fully automatic surveillance and control system. However, today's technology can provide only a very expensive and imperfect solution. Sensing and control technology is in an era of rapid development and a premature installation of an automated system may saddle on airport with a system which will be out of date by the time it is needed. Hence, a very careful study must be made of traffic rates, visibility conditions, and projected changes in the layout of runways and taxiways.

The voice communication channels of numerous airports are rapidly approaching saturation and modification of present-day control systems is required. The modifications should be made using a building-block approach. The following steps are pertinent:

a. Route selection by means of manual selective switching of high-intensity taxiway lights and route-indicating signs.

b. Introduction of manually controlled stop bars at runway/taxiway intersections.

c. Installation of airport surface detection radar to cover the entire airport complex.

d. Integrating the facsimile display of the taxiway lighting system and the radar displays.

e. Provision of manually operated stop bars and yield-right-of-way controls at taxiway intersections.

f. Automation of taxiway control.

g. Automation of ramp control.

5.4 Visibility Conditions

ICAO has classified the visibility conditions affecting the operational requirements of surface movement control system as follows [42]:

"Condition 1: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, and for personnel of control units to exercise control over all traffic on the basis of visual surveillance;

"Condition 2: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance;

"Condition 3: Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on the same taxiway but not at intersections by visual reference, and insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance;

"Condition 4: Visibility sufficient for the pilot to maintain the center line of the taxiway by visual reference, but insufficient to avoid collision with other traffic on the same taxiway or at intersections by visual reference or for personnel of control units to exercise control over all traffic on the basis of visual surveillance; and

"Condition 5: Visibility insufficient for the pilot to taxi by visual reference or for personnel of control units to exercise control over any traffic on the basis of visual surveillance."

The limits of visibility for these conditions are dependent upon such factors as airport size and complexity, aircraft size and taxiing speed, the taxiway guidance system, and the intensities of the lights involved. Typical limits are [42]:

Condition 1: Lower visibility limit is in the one to three mile range.

Condition 2: Lower visibility limit is an RVR of about 1200 feet (360 m) for a taxiing speed of 25 knots. Surveillance radar is required. A yield signal would be useful. The lower visibility limit can be lowered to about 700 feet (210 meters) RVR if the landing and/or taxiing lights of taxiing aircraft are turned on. This limit can be lowered further by reducing taxiing speeds (see below).

Condition 3: Lower visibility limit is about 500 feet (150 m) RVR. Taxiway intersection control will be required as well as surveillance radar. High intensity navigation lights will be required on the aircraft.

Condition 4: Lower visibility limit is an RVR of about 250 feet (75 m). Longitudinal separation of aircraft on the same taxiway will be required. The ratio of meteorological visibility to RVR and of the visual range of lower intensity lights to RVR is lower by day than by night. Thus for a given RVR, daylight conditions are limiting and a system which is adequate for daylight operations will be adequate for nighttime conditions.

A rational choice of the controls to be provided requires a detailed knowledge of the frequency of occurrence of low values of RVR and the aircraft movements expected in these lower RVR conditions. In particular a breakdown of the Category IIIB RVR conditions into several sub-sections is required. Data of the type shown in Figure 10 are required.

5.4.2 See-and-be-Seen Limits and Speed Control

Control of taxiing speeds may be required to prevent aircraft from overrunning stop bars, clearance bars, curves, and preceding aircraft on the taxiway. Hogg [41] has suggested the following speeds [41],

"CAT. II Maximum speed 25kn
CAT. IIIA Maximum speed 20kn
CAT. IIIB 100-200m RVR maximum speed 12kn

"As these can only be applied as an airport rule, the RVR on which they are based must be the lowest recorded anywhere on the airport. These speeds do have a safety margin but a further assessment of the maximum visibility gradient over every airport to which it is to be applied should be carried out to check if the margin is too small.

"The result of such a conclusion is that all aircraft operating in CAT. II and below should be fitted with taxi speed meters, and all aircraft operating in CAT. IIIB should have special high-intensity, high integrity tail lamps. The absence of these facilities necessitate that the controllers must accept more responsibility for aircraft separation and hence must reduce the airport's traffic rate, as this necessitates effectively block separation, a slow tedious and cumbersome procedure. All movements in visibilities below 100m RVR must of necessity be controller separated and hence the movement rate must be severely restricted."

5.5 Monitoring

ICAO Circular 148-AN/97 [42] states that:

"Surface movement guidance and control relies heavily upon lights for safe operations in reduced visibility and at night, and it is of vital importance that ATC should be aware of any discrepancies between the lighting selected and the lighting provided. Normally in good

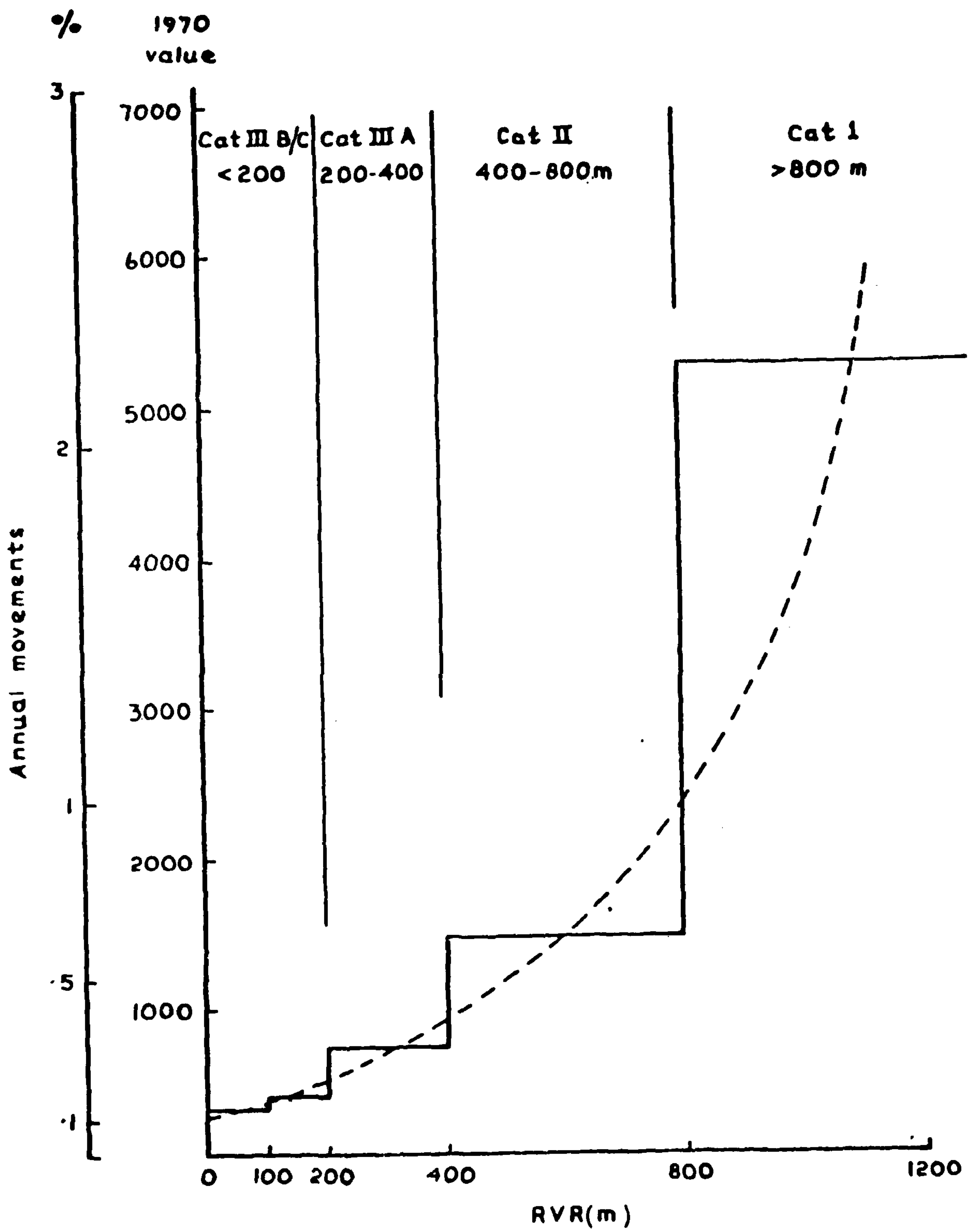

Figure 10. Movements affected by fog at Heathrow. (From Reference [41])

visibility conditions at night it is not difficult to see whether the switches thrown bring on the appropriate surface lights, the problems arise in reduced visibility when the lights are not visible to the controller. It is important that lighting display panels are so engineered that they constitute effective monitors of surface lighting. Many lighting control panels provide a tell-tale indication only of the lighting selected and do not indicate whether the lights are actually lit. A feed-back mimic may indicate whether a particular group of lights is on or not, but may not reflect individual light failures which could be significant for movement in low visibility. Power supply and circuit state indications can provide information on percentage light outage without showing the specific nature of the failures. Problems can arise from failure of lamps to go out, as well as from failure to light, on selection. Safe and efficient ground movement in low visibility demands a monitoring system so designed that the controller is speedily aware, and continuously reminded, of any lighting failure which could affect safety or cause taxiing difficulties in the area for which he has responsibility."

5.6 Sensors

The sensors of a fully automated guidance and control system must identify and track all movements on the manueuvering area, feeding the information obtained into a computer for processing. At present a block signalling system with sensors located at each block boundary to detect an aircraft approaching and crossing the boundaries is feasible. Such systems have been highly developed by the railways.

There are, however, several disadvantages to these systems. Among These are:

a. Number of blocks required:

   The large number of sensors required. Since only one aircraft or vehicle is permitted in a block, the blocks must be short if an acceptable movement rate is to be obtained. (The movement rate with the present Heathrow configuration would be unacceptable in clear weather).

b. Reliability and integrity:

   Not only must the sensors be very reliable but movements of vehicles must be confined to the pavement since entering or leaving the block without crossing over a sensor could destroy the logic of the data.

c. Cost and maintenance would be very high.

Today, the inductive-loop sensor appears to be the most satisfactory type of sensor [41, 43,]. Such units are in common use at highway intersections. However, there each sensors covers only one lane of traffic. In airport service, the width of the region covered may be 100 feet (30 m)

or more. Also they must respond to aircraft of all sizes (not only to the landing gear but also the fuselage) and to large and small vehicles and produce only one response per crossing. The presence of reinforcing rods in the pavement may present a sensitivity problem.

There is no satisfactory sensor today [43]. Considerable development and testing will be required.

5.7 Primary and Secondary Surveillance Radar

The ICAO Circular [42] states that:

> "Track-while-scan primary radar techniques allow an aircraft, once identified and labelled, to be automatically tracked by the radar with identity displayed. These techniques were, however, developed for air surveillance where most radar returns are from aircraft; this is not the case with a surface surveillance radar where most of the returns are from the ground or buildings. A simple transfer of the airborne target tracking technique to a ground application is not possible. Techniques for the primary tracking and labelling of surface surveillance radar have been proposed, but considerable research and development would be necessary before feasibility could be determined."
>
> "Secondary surveillance radar, relying on a response from the aircraft with a unique code format, provides the identity information required by the ground movement controller, but its volumetric resolution was designed for airborne separation standards of miles and, with standard interrogation methods, is unsuited to the separation in terms of metres to be expected on the aerodrome surface. Research has provided two possible answers:
>
> a. A selectively addressed secondary surveillance radar system/discrete address beacon system (ADSEL/DABS) components of secondary surveillance radar (SSR).
>
> b. Advanced techniques of interrogation and processing of transponder replies via multiple receivers, to overcome the limitations of conventional aircraft transponder fit.
>
> The chief advantage of b. is that it uses a signal source already accepted as a standard fitment on aircraft, while a. carries all the advantages of a selective address system and, additionally, offers a data transfer capability which could help with the communication problem, but it calls for an additional aircraft fit, which, by all precedent, would affect the time it takes to become agreed and established."

5.8 Cost

Based upon the RAE study, the adjusting for inflation and rate of exchange, the cost of an automated control system based upon block control would be of the order of $20,000,000 for an airport of the complexity of Heathrow. Annual maintenance costs would be about one tenth the installation cost.

5.9 The Human Factor

No matter how well an automated system is designed, and how reliable its components are made, there is always the possibility of human error. The author once saw an aircraft take a wrong turn at Heathrow under clear twilight conditions. The controller immediately switched circuits to bring the aircraft back to the designated route. This event demonstrates that an automated system must be designed so that an overrunning of a stop bar, the making of a wrong turn, or the failure to yield right of way will alarm both the pilot and the controller. Manual intervention will be required to restore normal operation.

6. SUMMARY

A state-of-the-art survey has been made of the development of taxiway guidance and control systems and the requirements of automated systems.

Comprehensive automated surface movement control systems using visual aids will require a sensor-triggered, computer-switched taxiway centerline and stop bar lighting system and a combined primary and secondary surface surveillance radar with more that one scanner location at most airports.

7. RECOMMENDATIONS

It is recommended that:

1. The U.S. establish a team to study the present and future needs of surface movement guidance and control with emphasis being given to the clear weather needs of high density airports and to the requirements for Category weather conditions.

2. The need for improvement of taxiway guidance and control in the U.S. is urgent.

3. The team should consider the implementation of a building-block concept in the improvement of taxiway guidance and control using the following blocks as a guide:

    a. Route selection by means of manual selective switching of taxiway centerline lights.

    b. Introduction of manually operated stop bars on entrances to Category II and Category III runways.

    c. Installation of sufficient airport surface surveillance radar to cover the entire airport.

    d. Integrating the facsimile display of the taxiway lighting system with the radar display.

    e. Provision of manually-operated stop bars and yield-right-of-way signals at taxiway intersections.

f. Automation of taxi guidance control.

g. Automation of ramp control.

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